



LANDSLIDES

INVESTIGATION AND MITIGATION

SPECIAL REPORT 247

A. Keith Turner
Robert L. Schuster
Editors

Transportation Research Board Special Report 247

Subscriber Category

IIIA soils, geology, and foundations

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competence and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The Transportation Research Board does not endorse products or manufacturers; trade and manufacturers' names may appear in this Special Report because they are considered essential to its object.

This report was sponsored in part by the National Science Foundation.

Transportation Research Board publications are available by ordering directly from TRB. They may also be obtained on a regular basis through organizational or individual affiliation with TRB; affiliates and library subscribers are eligible for substantial discounts. For further information, write to the Transportation Research Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

Copyright 1996 by the National Academy of Sciences. All rights reserved

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data

Landslides : investigation and mitigation / A. Keith Turner, Robert L. Schuster, editors.

p. cm. — (Special report / Transportation Research Board, National Research Council ; 247)

Includes bibliographical references and index.

ISBN 0-309-06151-2

ISBN 0-309-06208-X (pbk.)

I. Landslide hazard analysis. 2. Landslides. I. Turner, A. Keith, 1941- . II. Schuster, Robert L. III. Series: Special report (National Research Council (U.S.) Transportation Research Board) ; 247.

QE599.2.L36 1996

551.3'07—dc20

95-40780

CIP

Sponsorship of Special Report 247

Division A—Technical Activities

GROUP 2—DESIGN AND CONSTRUCTION OF TRANSPORTATION FACILITIES

Chairman: Michael G. Katona, U.S. Air Force Armstrong Laboratory

Study Committee on Landslides: Analysis and Control

Chairman: A. Keith Turner, Colorado School of Mines

David M. Cruden, J. Michael Duncan, Robert D. Holtz, Jeffrey R. Keaton, Verne C. McGuffey, Victor A. Modeer, Jr., Robert L. Schuster, Tien H. Wu, Duncan C. Wyllie

Liaison Representative

John L. Walkinshaw, Federal Highway Administration,
U.S. Department of Transportation

Transportation Research Board Staff

Robert E. Spicher, Director, Technical Activities

G.P. Jayaprakash, Engineer of Soils, Geology, and Foundations

Nancy A. Ackerman, Director, Reports and Editorial Services

Naomi C. Kassabian, Associate Editor

Karen White, Graphic Designer

COVER Damage to railroad line in Olympia, Washington, caused by slope failure after 1965 Seattle-Tacoma earthquake (photograph courtesy of G.W. Thorsen, Washington Department of Natural Resources). *Top inset:* October 1986 reactivation of Cucaracha landslide in Gaillard Cut, Panama Canal, which originally extended across canal (dredges had removed much of toe by time of photograph); white material in upper center is lime added to surface as remedial measure (photograph courtesy of Panama Canal Commission). *Bottom inset:* Recurring landslide on Colorado State Highway 133 at McClure Pass west of Aspen, spring 1993 (photograph courtesy of T.E. Taylor, Colorado State Patrol).

FRONTISPIECE Derailment of California Zephyr passenger train near Granby, Colorado, in April 1985 caused by minor landslide (see Figure 2-6, p. 18) (photograph courtesy of R. L. Schuster).

TITLE PAGE Inset: Railway and highway at Howe Sound, British Columbia, blocked by October 1990 rock fall, which originated approximately 300 meters above highway (photograph courtesy of D. Howard, Vancouver Sun). *Background:* detail from drawing by Alexandre Collin (1846) of landslides in clay slopes along French canals (see Figure 1-5, page 9).

CONTENTS

PART 1: Principles, Definitions, and Assessment

1 Introduction

A. Keith Turner and G.P. Jayaprakash

1. Intended Audience, 3
2. Definitions and Restrictions, 4
3. Historical Information Concerning Landslides, 4
4. Overview of Report, 10
- References, 11

2 Socioeconomic Significance of Landslides

Robert L. Schuster

1. Introduction, 12
2. Future Landslide Activity, 12
3. Economic Losses Caused by Landslides, 13
4. Landslide Casualties, 27
5. Positive Effects of Landslides, 31
6. Conclusions, 31
- References, 31

3 Landslide Types and Processes

David M. Cruden and David J. Varnes

1. Introduction, 36
2. Forming Names, 37
3. Landslide Features and Geometry, 40
4. Landslide Activity, 44
5. Rate of Movement, 49
6. Water Content, 52
7. Material, 52
8. Type of Movement, 53
9. Landslide Processes, 67
10. Summary, 71
- References, 71

4 Landslide Triggering Mechanisms

Gerald F. Wieczorek

1. Introduction, 76
2. Intense Rainfall, 76
3. Rapid Snowmelt, 80
4. Water-Level Change, 81
5. Volcanic Eruption, 83
6. Earthquake Shaking, 83
7. Summary, 86
- References, 87

5 Principles of Landslide Hazard Reduction

Robert L. Schuster and William J. Kockelman

1. Introduction, 91
2. Prerequisite Information, 92
3. Major Policy Options, 93
4. Approaches, 93
5. Landslide Insurance, 100
6. Multiple-Hazard Reduction, 101
7. Elements of National Program, 102
- References, 103

6 Landslide Hazard and Risk Assessment

Tien H. Wu, Wilson H. Tang, and Herbert H. Einstein

1. Introduction, 106
2. Description of Uncertainty, 106
3. Estimation of Hazard, 108
4. Decision Under Uncertainty, 110
5. Landslide Hazard Maps, 111
6. Historic Failure Rate, 112
7. Applications, 113
- References, 116

PART 2: Investigation**7 Organization of Investigation Process***A. Keith Turner and Verne C. McGuffey*

1. Introduction, 121
2. Field Investigation of Landslides, 121
3. Definition of Investigation Process, 121
4. Elements of an Investigation, 123
5. High-Quality Investigations, 127
6. Overview of Chapters 8–11, 127
- References, 128

8 Slope Instability Recognition, Analysis, and Zonation*Robert Soeters and Cornelis J. van Westen*

1. Introduction, 129
2. Principles of Hazard Zonation, 130
3. Remote Sensing in Slope Instability Studies, 140
4. Geographic Information Systems in Hazard Zonation, 163
- References, 173

9 Surface Observation and Geologic Mapping*Jeffrey R. Keaton and Jerome V. DeGraff*

1. Introduction, 178
2. Work Required Before Field Visitation, 179
3. On-Site Engineering-Geologic Investigations, 181
4. Surveys of Landslide Sites, 195
5. Interpretation and Data Presentation, 217
6. Guidance for Subsurface Investigations, 222
7. Correlation of Surface and Subsurface Data, 224
8. Additional Field Information, 225
9. Cost of Surface Investigations, 226
- References, 227

10 Subsurface Exploration*Verne C. McGuffey, Victor A. Modeer, Jr., and A. Keith Turner*

1. Introduction, 231
2. Planning Subsurface Investigations, 233
3. Reconnaissance Methods, 235
4. Surface-Based Geophysical Methods, 237
5. Test and Core Borings, 243
6. Borehole Logging, 248
7. Field Testing, 254
8. Treatment of Samples and Cores, 263
9. Investigation of Groundwater Conditions, 265

10. Data Presentation, 269

11. Summary, 274

References, 274

11 Field Instrumentation*P. Erik Mikkelsen*

1. Introduction, 278
2. Planning and Design, 279
3. Surface Measurement, 280
4. Ground-Displacement Measurement, 282
5. Groundwater Monitoring, 296
6. Data Recording and Transmission, 300
7. Example Projects, 303
8. Problems Preventing Further Development of New Instrumentation Technology, 313
- References, 314

PART 3: Strength and Stability Analysis**12 Soil Strength Properties and Their Measurement***Tien H. Wu*

1. Introduction, 319
2. General Principles, 319
3. Laboratory Measurement of Shear Strength, 322
4. In Situ Measurement of Shear Strength, 326
5. Shear Strength Properties of Some Common Soils, 327
- References, 332

13 Soil Slope Stability Analysis*J. Michael Duncan*

1. Introduction, 337
2. Mechanics of Limit Equilibrium Analyses, 337
3. Drained and Undrained Conditions, 341
4. Total Stress and Effective Stress Analyses, 342
5. Slope Stability Charts, 344
6. Detailed Analyses, 353
7. Back Analysis To Determine Soil Strengths, 363
8. Rapid Drawdown Analysis, 365
9. Analysis of Reinforced Slopes, 365
10. Three-Dimensional Analyses of Slope Stability, 367
11. Deformation Analysis, 368
12. Use of Centrifuge Experiments, 368
- References, 370

- 14 **Rock Strength Properties and Their Measurement**
Duncan C. Wyllie and Norman I. Norrish
1. Introduction, 372
2. Shear Strength of Fractures, 375
3. Laboratory Testing of Shear Strength, 381
4. Shear Strength of Fractured Rock Masses, 383
5. Rock Durability and Compressive Strength, 388
References, 389

- 15 **Rock Slope Stability Analysis**
Norman I. Norrish and Duncan C. Wyllie
1. Introduction, 391
2. Types of Rock Slope Failures, 392
3. Stereographic Analysis of Structural Fabric, 392
4. Planar Failure, 395
5. Wedge Failure, 402
6. Toppling Failure, 410
7. Circular Failure, 415
8. Other Failure Modes and Analytical Techniques, 418
References, 424

PART 4: Mitigation

- 16 **Important Considerations in Slope Design**
Jeffrey R. Keaton and George H. Beckwith
1. Introduction, 429
2. Environmental Conditions Affecting Slope Stability, 430
3. Material Properties and Site Characteristics, 433
4. Economic Constraints, 434
5. Other Design Constraints, 435
References, 437
- 17 **Stabilization of Soil Slopes**
Robert D. Holtz and Robert L. Schuster
1. Introduction, 439
2. Design Considerations, 439
3. Factor of Safety, 439
4. Design Procedures and Approaches, 440
5. Avoidance of the Problem, 440
6. Reduction of Driving Forces, 442
7. Increase in Resisting Forces, 451
References, 467

- 18 **Stabilization of Rock Slopes**
Duncan C. Wyllie and Norman I. Norrish
1. Introduction, 474
2. Planning Slope Stabilization Programs, 476
3. Rock Reinforcement, 482
4. Rock Removal, 490
5. Protection Measures Against Rock Falls, 493
6. Contracting Procedures, 500
References, 501

PART 5: Special Cases and Materials

- 19 **Residual Soils**
Philip C. Lambe
1. Introduction, 507
2. Saprolite Properties, 512
3. Pore Pressures, 515
4. Case Histories, 517
References, 523
- 20 **Colluvium and Talus**
A. Keith Turner
1. Introduction, 525
2. Slope Instability in Colluvium, 528
3. Slope Instability in Talus, 542
4. Subsurface Investigations, 545
5. Design Considerations for Colluvium, 546
References, 549
- 21 **Shales and Other Degradable Materials**
John L. Walkinshaw and Paul M. Santi
1. Introduction, 555
2. Geological Considerations, 555
3. Identification and Classification, 558
4. Engineering Design Considerations, 563
5. Conclusion, 573
References, 574
- 22 **Hydraulic Tailings**
Steven G. Vick
1. Introduction, 577
2. Characterization and Properties, 577
3. Slope Stability and Environmental Issues, 580
4. Failure of Tailings Impoundments, 582
5. Mitigation Measures, 583
References, 583

23 Loess*Jerry D. Higgins and Victor A. Modeer, Jr.*

1. Introduction, 585
 2. Literature Review, 586
 3. Review of Cut-Slope Design Practice, 591
 4. Failure Mechanisms, 593
 5. Site Characterization, 599
 6. Laboratory Testing, 600
 7. Field Testing, 601
 8. Loess Slope Design, 601
 9. Drainage Design, 603
 10. Construction-Control Considerations, 604
 11. Maintenance and Repair, 604
- References, 605

24 Soft Sensitive Clays*Guy Lefebvre*

1. Introduction, 607
 2. Description of Sensitive Clay Deposits, 608
 3. Valley Formation and Groundwater Regime, 610
 4. Stability Analysis, 612
 5. Establishing Risk of Retrogression, 615
 6. Conclusions, 617
- References, 617

25 Permafrost*Rupert G. Tart, Jr.*

1. Introduction, 620
 2. Occurrence of Permafrost, 622
 3. Characteristics of Frozen Ground, 623
 4. Types of Permafrost Slope Movements, 629
 5. Methods for Controlling Stability of Permafrost Slopes, 638
- References, 643

Appendix A

Stereographic Projections for
Structural Analysis, 647

Appendix B

Metric Conversion Table, 650

Author Biographical Information, 653

Author and Subject Index, 659